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CRRESPRO DOCUMENTATION

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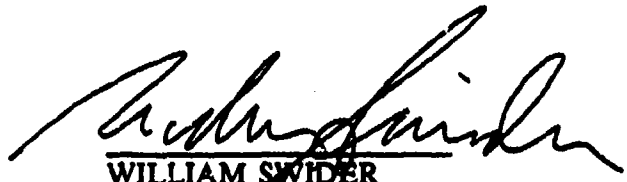

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13. ABSTRACT (Maximum 200 words)

This technical report documents the software package CRRESPRO developed by the Phillips Laboratory. The CRRESPRO utility calculates proton omnidirectional fluence and integral omnidirectional fluence over the energy range 1-100 MeV for orbits specified by the user. Proton fluence is calculated from proton flux models created using data measured by the proton telescope (PROTEL) on the Combined Release and Radiation Effects Satellite (CRRES), which flew in a geosynchronous transfer orbit for 14 months during solar maximum. Because the March 1991 magnetic storm caused a reconfiguration of the inner magnetosphere resulting in double proton belts for certain energies, two CRRES models were constructed. The quiet (single proton belt) model uses PROTEL data from July 1990 to March 1991, and the active (double proton belt) model uses data from March 1991 to October 1991. CRRESPRO is best applied to orbits with altitudes greater than 1000 km. Unlike its sister program, CRRESRAD, CRRESPRO gives 100 percent coverage for orbits of any inclination.

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Many people contributed to the success of the Proton Telescope (PROTEL) and the creation of CRRESPRO. E.G. Mullen headed the CRRES/SPACERAD team and has insisted on user-friendly data products. CRRESPRO and its sister utility, CRRESRAD, were his ideas. PROTEL was assembled by Edward Boughan of MIT with the support of Dr. David Hardy, Kevin Riehl, and Kristina Lynch of Phillips Laboratory. Dave Fischi of MIT developed the flight software. Kristina Lynch, Robert Redus, Michael Violet, and Kevin Riehl were instrumental in the design, fabrication, testing and calibration, launch, orbital operations, and post flight data analysis. The successful testing and operations of PROTEL were supported by George Murphy, Dave Pendleton, Marilyn Oberhardt, Kevin Ray, and Tim Schumaker of Phillips Laboratory. Many people at Consolidated Space Test Center (CSTC) commanded the satellite and gathered the data which made PROTEL and the CRRES mission a success. Carl Hein and Jim Bass of RADEX developed a Monte Carlo method for measuring detector response to >100 MeV protons, developed routines for mapping equatorial data down the field lines and fitting pitch angle dependence to functional forms, and modified LOKANGL to run on the IBM PC. The Olson-Pfitzer Static and the IGRF85 magnetic field models were modified to run on the IBM PC by K.A. Pfitzer of McDonnell Douglas Space Systems Corporation. Dan Madden of Boston College processed the PROTEL data. The CRRESRAD software, on which CRRESPRO is based, was written by Kevin Kerns. Jabin Bell and Michael Violet of Phillips Laboratory were most helpful with modifying the CRRESRAD code to form CRRESPRO.

CRRESPRO Documentation

1. OVERVIEW

CRRESPRO predicts proton omnidirectional fluence per year and integral omnidirectional fluence per year at selected energies in the range 1 - 100 MeV for an orbit specified by the user. It closely parallels its counterpart, CRRESRAD, which predicts dose behind four thicknesses of hemispherical aluminum shielding. Likewise, this documentation closely follows the CRRESRAD documentation. The CRRESPRO software uses flux models created from data collected by the proton telescope (PROTEL) on board the Combined Release and Radiation Effects Satellite (CRRES) flown from 25 July 1990 to 12 October 1991 during solar maximum. CRRES was in a geosynchronous transfer orbit with an inclination of 18°, a perigee of 350 km, and an apogee of 33000 km. It traversed the radiation belts twice per orbit with a period of 9 hours 52 minutes. In March 1991, a magnetic storm caused a reconfiguration of the inner magnetosphere, resulting in, among other features, double proton belts forming over a certain energy range. Because of this change, two CRRES models were created. The quiet model uses data from July 1990 to March 1991, and the active model uses data from March 1991 to October 1991. Note that in this documentation and the CRRESPRO software, "quiet" refers to the period from July 1990 to March 1991 (single proton belt) and "active" refers to March 1991 to October 1991 (double proton belt). Quiet and active as used here for the inner radiation belt have no correspondence to quiet and active as determined by Kp. In fact, the average Kp for the two CRRES periods was the same, namely 2.2.

The CRRESRAD software, which was released by this office (PL/GPSP) in 1992, was developed when dose measurements on CRRES and the Defense Meteorological Satellite Program (DMSP) showed that the current NASA models used to predict dose for satellite design and orbit determination are not

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always adequate (Gussenhoven et al., 1987, 1991a, 1991b). A major geomagnetic storm occurred in late March 1991 following an intense solar proton event during which strong shock fronts hit the magnetosphere. The result of the shock passages was a change in the magnetosphere to a more active configuration (Mullen et al., 1991 and Blake et al., 1992). Before the March storm, dose predicted by the NASA models for protons below 100 MeV agreed very well with measured dose in the inner zone, but dose predicted by the NASA models for electrons was larger than the measured dose by as much as an order of magnitude. After the storm, a second energetic proton belt and a third energetic electron belt were formed in the slot region where there had previously been little radiation. During this period, major differences exist between the CRRES and NASA models (Brautigam, 1992; Gussenhoven, et al., 1992).

A well designed, well calibrated proton detector can be used to create accurate, pitch angle dependent, empirical proton flux models on the magnetic equator as a function of L shell (see below) for a wide energy range. These average fluxes can then be propagated down the relatively stable magnetic field lines of the inner magnetosphere to extend the models outside the range of the satellite. A utility such as CRRESPRO will give the total proton fluence predicted by the model at given energies for an arbitrary satellite orbit. Then, with a transport code, the results of the model can be used to determine dose behind any type of shield. Furthermore, different models, such as the CRRES proton models and the NASA proton models, can be directly compared for differences in intensity, pitch angle dependence, and spectral shape.

Such a comparison was made by Gussenhoven, et al. Among the findings of the comparison are two regions in the inner magnetosphere that are populated by high energy protons. The inner, stable region exists below L = 1.8. Beyond L = 1.8, there exists a population that was previously thought to be a continuous extrapolation of the inner population, as is shown by the NASA AP8MAX model. However, the PROTEL measurements show that beyond L = 1.8 a new population can be brought in during periods of extreme solar wind conditions and apparently added to the existing population. This presents a radiation hazard that can continue for months and is not dealt with by the NASA models. It is possible that AP8MAX is an average of the two conditions measured by CRRES. (Gussenhoven et al., 1993)

CRRESPRO requires an 80386 or 80486 DOS based computer with a math coprocessor, a color VGA card, and a hard drive. A printer is not needed, but it is useful. The active directory must be the one containing CRRESPRO.EXE and its support files. CRRESPRO is run by typing "**CRRESPRO**" on the command line. The user will be queried for the name of the orbit to be evaluated. This name will be used for all of the data files subsequently created for this orbit. The data files can be written to another directory by adding the path to the name. For example, to run an orbit called "Sample" and store the data in "C:\Orbits\", the name would be specified as "C:\Orbits\Sample". No extension can be given

in the name as default extensions are used. An ASCII README file is included with the CRRESPRO software. To read this file enter "**TYPE README | MORE**" on the command line and press <enter>. README documents recent updates to the software and has a directory list of the files included with CRRESPRO. As a precaution against viral contamination, make sure the ".EXE" files are the same size and date as given in the README file. A sample session for determining the fluence from a CRRES-like orbit is shown in Appendix A.

2. FLUX MODEL

The motion of the high energy ions and electrons that cause dose deposition in satellites in Earth's magnetosphere is determined almost entirely by Earth's magnetic field. These particles are trapped by the magnetic field, and are constrained to bounce back and forth between the north and south poles along magnetic field lines. The paths these particles take are referred to as "shells." Because these particles are constrained to move along magnetic field lines, fluence resulting from these particles is best ordered by specifying position with magnetic field parameters instead of using spatial coordinates. The magnetic field parameters used for the flux model are the McIlwain L parameter (McIlwain, 1961), which is referred to hereafter as L shell, and B/B_0. In a dipole magnetic field the L shell of a given point in space is the equatorial radial distance in Earth radii (R_E) of the field line passing through the given point. Earth's magnetic field has some non-dipole components, and L shell is calculated by determining which dipole field line the actual field line would correspond to if Earth's magnetic field were relaxed to a dipole field. B/B_0 is the ratio of the magnetic field magnitude at a point in space divided by the minimum magnitude of the magnetic field on the same field line. The field is strongest near the poles and weakest near the equator so that $B/B_0 = 1.0$ is near the equator and maximum B/B_0 is closer to the poles. For a dipole field, B/B_0 is a function only of magnetic latitude. The solid lines in Figure 1 show L shells 2, 3, 4, 5, and 6 of a dipole magnetic field centered in Earth. The dotted lines show constant B/B_0 contours and their magnitude spaced every 10° in an Earth-centered dipole field between -40° and +40° magnetic latitude. Chapter 5 of the *Handbook of Geophysics and the Space Environment* (Spjeldvik and Rothwell, 1985) contains a more complete description of Earth's magnetosphere and radiation belts.

The Olson-Pfitzer static external magnetic field model and the IGRF85 internal magnetic field model were used to calculate the L shell and B/B_0 values when binning the CRRES flux data. The IGRF85 model specifies the magnetic field that comes from currents inside Earth (IAGA Division I, Working Group 1, 1986). This field is nearly dipolar with an 11.5° tilt and 436 km offset with respect to Earth's spin axis and is slowly changing with time (Knecht and Shuman, 1985). The IGRF model accounts for

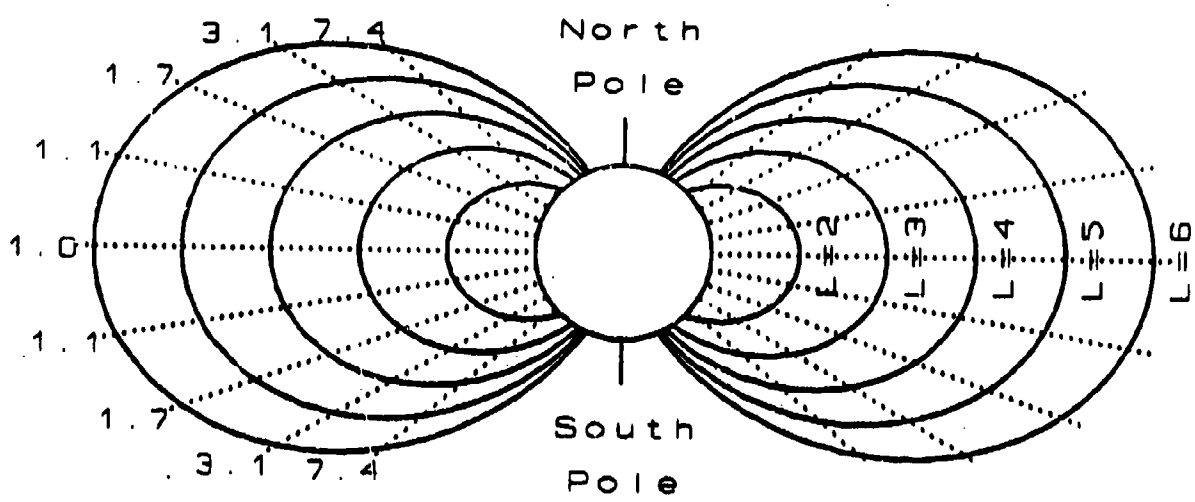

Figure 1. L Shells 2, 3, 4, 5, and 6 (Solid Lines) and Lines of Constant B/B_0 = 1.0, 1.1, 1.7, 3.1, and 7.4 (Dashed Lines) in a Dipole Field Centered in Earth.

the slow time variation of the field as well as the tilt and non-dipole contributions to the field. The Olson-Pfitzer static model (Olson and Pfitzer, 1974) predicts changes in the magnetic field caused by currents in the magnetopause, the ring current, and the magnetosphere's tail. The model also accounts for the tilt of Earth's dipole with respect to the Earth-Sun line. The external currents that contribute to the magnetic field change with variations in the solar wind and magnetospheric activity. The static model assumes these currents do not change and uses values from average quiet conditions. We should note that the Olson-Pfitzer external field makes no contribution inside an L shell of 2.4.

The flux models used by CRRESPRO are based on *in situ* flux measurements made by CRRES. Their construction is described in Gussenhoven et al. (1993), and is briefly reviewed here. The instrument used to measure flux on CRRES was the Proton Telescope (PROTEL). PROTEL had two detector heads, which together measured protons from 1 to 100 MeV in 24 energy steps, giving a complete spectrum every 1.024 seconds. The angular resolution of the detector low (high) energy head was $\pm 10° \times \pm 10°$ ($\pm$ 12° x $\pm$ 17°). A full description of PROTEL is available in Violet et al. (1993) and Lynch et al. (1989). The PROTEL detectors comprised detector stacks and a logic system that required single or double coincidence to verify that the proper energy particle is counted. In addition, both active and passive shielding were used around much of the detector stack. The detectors were extensively calibrated prior to launch. During calibration, we found that energetic protons (>60 MeV) incident over a large angular range with respect to the detector axis could degrade sufficiently in the shielding, pass through the necessary angle in the detector stack, and be counted. This contamination was found to be significant enough for very hard spectra, such as occurs for L shells between 1.1 and

1.7, to require correction. We devised a correction scheme based on the assumption of an empty atmospheric loss cone. The correction scheme was consistent with the contamination predicted by a computer model of PROTEL combined with a Monte Carlo ray tracing code developed by Hein (1993). For details of the correction scheme see Gussenhoven et al. (1993).

The loss cone method of correcting for high energy proton contamination was excessive for the two lowest channels of each detector head, for which there was no or only single coincidence in the counting scheme. Therefore, in the region of L = 1.1 to 1.7, a cubic spline extrapolation from (interpolation between) neighboring channels was made to obtain values for the 1.5 and 2.1 MeV channels (5.7 and 8.5 MeV channels). These corrections were made on the model average values, not point by point.

One channel (15.2 MeV) had significantly lower sensitivity than the other channels and one channel was an overlap channel at 8.5 MeV. To avoid both redundancy and the appearance of discontinuities in differential and integral spectra at certain L values, the 8.5 and 15.2 MeV channels were not used.

For the CRRES proton models, a data base of differential number flux values on the magnetic equatorial plane was created using each PROTEL data point. The *in situ* values were mapped point by point to the magnetic equator conserving the first adiabatic invariant in the combined IGRF85 and Olson-Pfitzer quiet magnetic field model. The equatorial data were averaged by channel for each leg of each orbit in L shell bins of extent 1/20th R_E and pitch angle bins of width 5°. The loss cone corrections for high energy contamination were made on each orbit leg average. The equatorial data from all orbits occurring before (after) the March 1991 storm were then combined in the same L and pitch angle bins to create the CRRES quiet (active) proton model.

The proton inner radiation belt at a given energy is expected to fall off to an insignificant value at some L. However, the sporadically occurring solar protons take over the flux average at some minimum L that represents their deepest penetration into the magnetosphere. Although we retained the solar particle effects in the dose models, they are omitted from the proton belt models. We feel that for predictive purposes the solar protons are better represented by probability rather than average models and will be handled separately at a later time. In examining the array of average flux values in L and pitch angle for each energy channel, it is generally clear where the fluxes begin to level off in L and transition from trapped pitch angle distributions to solar particle event (SPE) isotropic distributions. Identification of the boundary between the two populations was done "by hand" for each energy channel of each model. All but the 1.5 MeV channel had cutoff L values below 5.50 R_E. Thus, 5.50 is the maximum L value of the CRRES inner belt proton models.

To compute the total proton fluence for an arbitrary satellite orbit, it is necessary to completely fill the B/B_0 and L space out to L = 5.50 with omnidirectional fluxes at each grid point using the equatorial model data. We retain the bin width of 1/20th R_E in L and project down the field line to B/B_0 values

corresponding to 2° steps in magnetic latitude in a dipole magnetic field from 0°to 68°. This leads to an array size of 90 (L shell) by 34 (B/B_0).

In summary, we have created two proton models from the CRRES PROTEL data base: a quiet model using data acquired before the March 1991 storm and an active model using data acquired after the storm. Each model potentially consists of twenty-four sub-models, one for each energy channel. As discussed above, we eliminate one of the 8.5 MeV channels and the 15.2 MeV channel. This results in 44 different flux model files, which are stored in binary format in "FLUX_MOD.00" through "FLUX_MOD.43". A 45th model file representing the NASA AP8MAX integral flux for protons with energy >90.4 MeV is also stored in the same format and called "NASA_MOD.00". This file is used to determine the integral omnidirectional fluence for the protons with energies over 90.4 MeV, which is the upper limit of the integral fluence calculations from the CRRES models. The integration parameters are discussed in Section 3, "Methods of Calculation".

3. METHODS OF CALCULATION

PROTEL's 24 energy channels have the following lower and upper boundaries and midpoint energies. The flux models are stored in the FLUX_MOD.## files indicated in the two columns on the right.

Energy Channel Parameters (MeV)				FLUX_MOD.## file	
Channel	E_{lo}	E_{mid}	E_{hi}	Quiet	Active
1	1.0	1.5	2.1	FLUX_MOD.00	FLUX_MOD.01
2	2.0	2.1	2.3	FLUX_MOD.02	FLUX_MOD.03
3	2.2	2.5	2.8	FLUX_MOD.04	FLUX_MOD.05
4	2.8	2.9	3.2	FLUX_MOD.06	FLUX_MOD.07
5	3.1	3.6	4.1	FLUX_MOD.08	FLUX_MOD.09
6	3.9	4.3	4.8	FLUX_MOD.10	FLUX_MOD.11
7	4.6	5.7	7.0	FLUX_MOD.12	FLUX_MOD.13
8	7.3	8.4	9.4	no FLUX_MOD.## files	
9	6.0	6.8	7.7	FLUX_MOD.14	FLUX_MOD.15
10	7.5	8.5	9.6	FLUX_MOD.16	FLUX_MOD.17
11	9.3	9.7	10.2	FLUX_MOD.18	FLUX_MOD.19
12	9.9	10.7	11.5	FLUX_MOD.20	FLUX_MOD.21
13	11.2	13.2	15.2	FLUX_MOD.22	FLUX_MOD.23

Energy Channel Parameters (MeV)				FLUX_MOD.## file	
Channel	E_{lo}	E_{mid}	E_{hi}	Quiet	Active
14	14.7	15.2	15.9	no FLUX_MOD.## files	
15	15.5	16.9	18.3	FLUX_MOD.24	FLUX_MOD.25
16	18.0	19.4	20.8	FLUX_MOD.26	FLUX_MOD.27
17	25.3	26.3	27.2	FLUX_MOD.28	FLUX_MOD.29
18	26.1	30.9	35.6	FLUX_MOD.30	FLUX_MOD.31
19	34.9	36.3	37.7	FLUX_MOD.32	FLUX_MOD.33
20	37.8	41.1	48.1	FLUX_MOD.34	FLUX_MOD.35
21	44.3	47.0	53.5	FLUX_MOD.36	FLUX_MOD.37
22	53.3	55.0	62.1	FLUX_MOD.38	FLUX_MOD.39
23	62.1	65.7	73.1	FLUX_MOD.40	FLUX_MOD.41
24	73.1	81.3	100.0	FLUX_MOD.42	FLUX_MOD.43

Channels 8 and 14 were omitted from all calculations.

The models give differential omnidirectional flux. To calculate differential omnidirectional fluence per year for an orbit input by the user, the time in seconds spent in each (L, B/B_0) bin is calculated by TIMEBINS.EXE, and the differential flux for each bin is multiplied by the time in seconds spent in that bin. The figures for the individual bins are summed. The resulting figure is then multiplied by (seconds per year / sum of time in seconds for all bins).

Integral omnidirectional fluence is $\int_{E_1}^{E_2} J(E)\,dE$, where J(E) is the differential omnidirectional fluence for energy E. The integration is approximated using rectangular steps, so that integral omnidirectional fluence = $\sum_{ch_i}^{ch20} F(E_i)\,\Delta E_i$, where $F(E_i)$ is the differential omnidirectional fluence at the average energy of channel ch_i. Because of overlapping energy ranges, channels 5 and 15 were omitted from the integral omnidirectional fluence calculation (in addition to channels 8 and 14 which are omitted from all calculations) and new boundaries were set up to prevent multiple contributions from the same energy. The integration summation for a channel ch_i begins at the lower boundary of that channel and ends at the new upper boundary of the highest energy channel, which is now channel 20 with an upper boundary of 90.4 MeV. It is left for the user to interpolate between energies if desired. The energy bounds and ΔEs used in the integrations follow.

	Integration Parameters (MeV)				
Channel #	E_{lo}	E_{mid}	E_{hi}	ΔE	
1	1.1	1.5	1.9	0.8	
2	1.9	2.1	2.3	0.4	
3	2.3	2.5	2.7	0.4	
4	2.7	2.9	3.1	0.4	
5	3.1	4.3	5.5	2.4	
6	5.5	5.7	5.9	0.4	
7	5.9	6.8	7.7	1.8	
8	7.7	8.5	9.3	1.6	
9	9.3	9.7	10.1	0.8	
10	10.1	10.7	11.3	1.2	
11	11.3	13.2	15.1	3.8	
12	15.1	19.4	23.7	8.6	
13	23.7	26.3	28.9	5.2	
14	28.9	30.9	32.9	4.0	
15	32.9	36.3	40.2	7.3	
16	40.2	41.1	43.2	3.0	
17	43.2	47.0	50.8	7.6	
18	50.8	55.0	59.2	8.4	
19	59.2	65.7	72.2	13.0	
20	72.2	81.3	90.4	18.2	

4. LOGICAL FLOW OF CRRESPRO

Figure 2 shows a flow diagram of the CRRESPRO execution. The solid arrows indicate the direction of flow, and the dashed arrows indicate the input and output at each step. After each logical step, CRRESPRO stops and presents the user with information about what it will be doing next, then waits for a key to be pressed before continuing.

First the user must enter the name of the orbit. This name will be used with all the files generated by CRRESPRO. No extension can be given with the name, but a path can be specified with the name if the files are to be written to some other directory. In Figure 2, the input name is represented by "?NAME?". First time users of CRRESPRO should type "**CRRESPRO**" on the command line. CRRESPRO

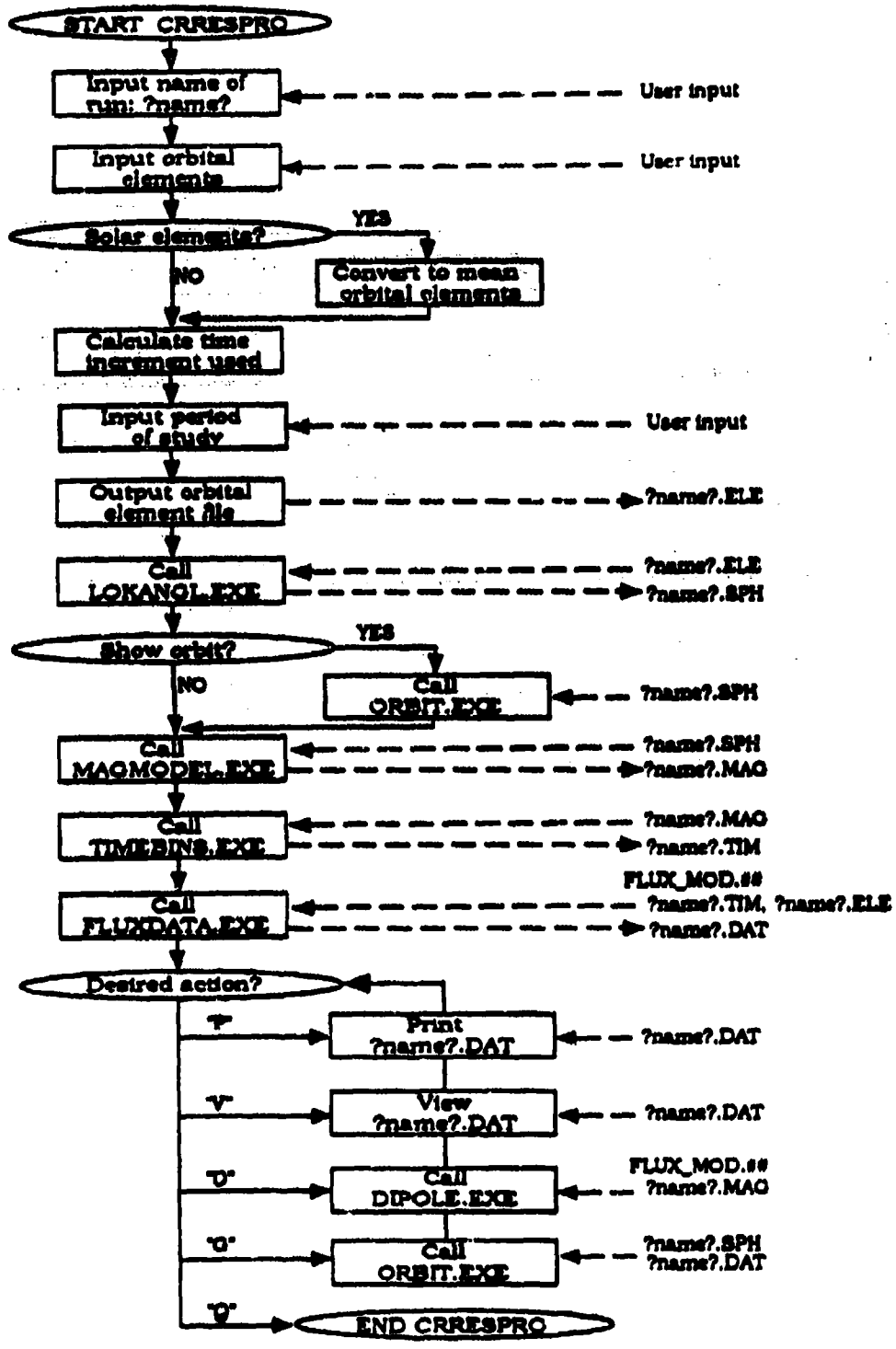

Figure 2. Simplified Flow Diagram of CRRESPRO. Solid Arrows Refer to Logical Flow, and Dashed Arrows Refer to Input and Output at Each Step.

will query the user for the name when it runs. (If files from a previous CRRESPRO run with the same name exist, CRRESPRO will ask the user if these files should be used.) A second option for users familiar with CRRESPRO is to include the name on the command line by typing "CRRESPRO ?NAME?." When this option is used, CRRESPRO does not stop to tell the user what it is doing or wait for user input. This allows long runs taking many hours to be done without requiring the user to respond to the CRRESPRO prompts. In this mode, any intermediate files that exist with the given name will automatically be used. Note: If a previous CRRESPRO orbit of the same name was interrupted during execution and the resulting files still exist, an error will result. The user should remove the old files or choose a new name for the orbit.

Next, CRRESPRO prompts the user for the orbital elements. These elements describe the orbit to be tested. Only orbits for times from day 1, 1985 to day 365, 1999 can be used. There are three options for specifying orbital elements:

Position and Velocity: The elements for position, r_x, r_y, r_z, and velocity, v_x, v_y, v_z, are specified in km and km/sec using the Earth Centered Inertial (ECI) coordinate system. Time is given in year, day of year, hours, minutes, and seconds and must be fall between the start of day 1, 1985 and the end of day 365, 1999.

Mean Orbital Elements: Inclination, right ascension of the ascending node, argument of perigee, and mean anomaly are specified in degrees, mean motion is specified in revolutions per day, and eccentricity is specified. Time is given in the same format as for the position and velocity elements.

Solar Elements: Inclination is specified in degrees, while altitudes of apogee and perigee are specified in km assuming R_E = 6378 km, and local times of apogee and maximum inclination are specified in hours. These elements are useful to scientists and engineers concerned with the location of an orbit with respect to the sun and to those who are not familiar with the standard orbital elements. The solar elements are not a full set of elements because there are only five elements (besides time) to input. The sixth element results from the assumption that the orbit is at apogee at the time for which the elements are specified. Local time of apogee of 12.0 indicates that the satellite is at apogee directly between the sun and Earth. Local time of maximum inclination indicates the local time where the geographic latitude of the satellite is at a maximum positive value. Default values of 12.0 and 18.0 are used respectively for the two local times, but these values may be changed. A six hour difference between the local

time of apogee and the local time of maximum inclination causes apogee to be at 0° geographic latitude. Oftentimes this arrangement results in the highest fluence since the highest proton concentration is near the magnetic equator, close to the geographic equator. There are other cases where the 6-hour difference does not result in the highest fluence. One example is an elliptical polar orbit with apogee in the equatorial slot region. The format of the given time is as specified for the position and velocity elements. The solar elements cannot be used by LOKANGL.EXE directly, so CRRESPRO converts solar elements into mean orbital elements. (LOKANGL.EXE is described below; see Appendix C for calculations.)

The elements are checked to make sure the orbit is not hyperbolic and perigee is not below 200 km (see Appendix C). The time step used in the study is chosen so that the orbit will sweep ~2° arc at perigee in a single time step (see Appendix C). The user then inputs the start time (between day 1 1985 and day 365 1999) and length of the study. The elements are written to an ASCII file called ?NAME?.ELE. After the user is done entering the set of elements, CRRESPRO waits for "D" to be pressed.

CRRESPRO calls LOKANGL.EXE, which reads the element file and generates an ephemeris file, ?NAME?.SPH, which contains geographic position. The position is calculated at each time increment in the specified period of study. Appendix D contains a description of the ?NAME?.SPH file. LOKANGL.EXE is used at the Phillips Laboratory Geophysics Directorate to predict positions of Earth satellites using orbital elements as an input. The code was modified by RADEX Inc. for use on the IBM PC. Contact this office (PL/GPSP) for information on the format of the ?NAME?.ELE file as well as a detailed description of LOKANGL.EXE. LOKANGL.EXE calculates the position of an Earth satellite using a perturbation expansion with the second and third zonal harmonics of Earth's gravitational field. It is not considered accurate for times more than 100 days from a specified orbital element. LOKANGL.EXE cannot evaluate hyperbolic or parabolic orbits or orbits where the radius becomes less that one Earth radius.

When LOKANGL.EXE is finished, CRRESPRO will give the user the option to view the orbit by calling ORBIT.EXE. Appendix E contains a description of ORBIT.EXE. If the file name was given on the command line, CRRESPRO will not give the option to view the orbit and will proceed on to the next step.

CRRESPRO calls MAGMODEL.EXE (see Appendix F) to convert the geographic coordinates in ?NAME?.SPH into magnetospheric coordinates that are put into the binary file ?NAME?.MAG, also described in Appendix D. The routines used by MAGMODEL.EXE to calculate L shell and B/B_0 were developed for the Air Force by Karl Pfitzer at McDonnell Douglas Space Systems Corp (Pfitzer, 1991). The IGRF85 model used by MAGMODEL.EXE is only valid for times after the start of day 1, 1985.

TIMEBINS.EXE is called next by CRRESPRO. This program reads the data in the magnetospheric ephemeris file and interpolates between points using a cubic spline to determine how much time the orbit spends in each of the bins defined for the flux models. The resulting array is written to the binary file ?NAME?.TIM.

CRRESPRO then calls FLUXDATA.EXE. This program reads in the times in each bin from ?NAME?.TIM and calculates the differential and integral omnidirectional fluence per year as explained in Section 3, "Methods of Calculation". FLUXDATA assumes that the first 44 files (## = 00-43) are the standard flux files; these files should not be renamed. Any other FLUX_MOD.## files found in the active directory will also be integrated and included in the output. The integrated data is output to a formatted ASCII file called ?NAME?.DAT. Appendix F shows the contents of SAMPLE.DAT which was generated in Appendix A. The top section gives the name, orbital elements, and the times of the study. After the time of study, the amount of the orbit (by time) not covered by the flux bins is given. An orbit similar to the CRRES orbit is used in SAMPLE.DAT. Since the proton models extend only to L = 5.5, part of the orbit is out of range of the model. For SAMPLE, this is 44 percent (by time), as indicated. With the exception of the 1.5 MeV channel, the flux bins not covered by CRRESPRO would make no contribution to the fluence. (See Section 2, "Flux Models".) The next part of the CRRESPRO output is a table showing differential omnidirectional fluence per year for the quiet and active periods. This is followed by a table showing integral omnidirectional fluence per year for the quiet and active periods. The first 44 FLUX_MOD.## files are used to produce the tables. The file NASA_MOD.00 is accessed to produce the final line of the CRRESPRO output, which shows the integral omnidirectional fluence for protons with energies >90.4 MeV.

At this point CRRESPRO is done with calculations and provides several options to view the data. Pressing "P" calls the DOS command "COPY ?NAME?.DAT PRN," which will print the ASCII file ?NAME?.DAT. Pressing "V" displays the file on the screen. "G" graphs the orbit using ORBIT.EXE. "D" graphs the orbit superimposed on the flux models using DIPOLE.EXE (see Appendix E), and "Q" quits CRRESPRO. A benchmark file is created by CRRESPRO which shows how long each of the different utilities took to run. This file has the name ?NAME?.BEN and is discussed in more detail in Appendix A.

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Appendix A

Sample Session

Type:

CRRESPRO <Enter>

Press any key once you have read the information on the screen. You are now asked for a file name. Here we use "Sample" as the file name. Type:

Sample <Enter>

Press any key once you have read the information on the screen. Press "S" to select solar elements. On the next screen we specify an orbit that is very similar to the orbits used by CRRES. Enter the solar elements and the time for which those elements apply:

year = **1991**
day = **130**
hour = **8**
minute = **0**
second = **0**
Inclination = **18**
Perigee = **350**
Apogee = **33000**

Leave the two default local times as they are at 12 and 18. This causes the satellite to be at apogee at 12:00 and at maximum inclination at 18:00 local time. (See Section 3 for the applicable logic.) If you enter something incorrectly, you can tab back to that line and enter it again. Pressing "x" then <Enter> on a line will delete it. When you are done press "D." At the next screen enter the time of the study:

year = 1991
day = 130
hour = 8
minute = 0
second = 0
length = 1 (days)

The time of the study can differ from the time entered previously for the element information. Press "D" when you are done.

A message will appear on the screen estimating the calculation time for a 66 Mhz 80486 computer. In this case the fluence will take about 1.1 minutes to calculate. The actual time required will vary with the speed of the computer and the type of orbit. In general, lower altitudes take longer than higher altitudes, elliptical orbits take longer than circular, and high inclination orbits take longer than low inclination. If you wish to terminate the program at this point press "N;" otherwise press "Y" to continue, and then press any key once you have read the information on the screen.

The code LOKANGL.EXE will execute. In the upper left corner of the screen is written "00001.1" which is the estimated time to completion in minutes. Below it is written the actual execution time. Once LOKANGL.EXE is done executing, CRRESPRO will ask if you would like to see the orbit. Press "Y" to execute ORBIT.EXE which shows a view of the orbit. The view in the lower right looks down on Earth's north pole with the sun towards the top. The other two images show side views, looking along X and Y. The orientation of the axes on these views follows standard drafting conventions. Press "Q" to quit ORBIT.EXE, then press any key after you have read the information on the CRRESPRO screen.

The code MAGMODEL.EXE will execute. The actual execution time (upper left corner of screen) does not start from zero, but begins where it left off when LOKANGL.EXE was finished executing. When MAGMODEL.EXE is through, press any key after reading the information on the screen.

The code TIMEBINS.EXE will execute. This code runs faster than LOKANGL.EXE or MAGMODEL.EXE. When it is done, press any key after reading the information on the screen.

The code FLUXDATA.EXE will execute. The time taken by this code does not depend on the size of the run. When it is done, read the information on the screen then press any key.

You now have several options for viewing the data. If you have a printer, press "P" to get a printout. (Appendix F is a copy of the printout of the file SAMPLE.DAT.) You can press "V" to see the output on the screen. "Q" will return you to the menu. Pressing "G" calls ORBIT.EXE to show the orbit plot again. Notice that more information is displayed in the upper left corner now that the job is complete. This information comes from the header in SAMPLE.DAT. "D" executes DIPOLE.EXE which shows the orbit track through the radiation belts. The orbit track is plotted entirely in the upper quadrant. Although this may at first seem unnecessarily confusing, it does allow one to use the lower quadrant to view the radiation belt intensities without orbit track obstruction. Notice that for "Sample." part of the orbit is outside the high L limit of 5.5. With the exception of the 1.5 MeV channel, this does not mean that the calculation is missing protons from the radiation belts. The statement on the printout indicating that 44.0 percent of the orbit is out of range reflects the time spent outside the maximum L = 5.5, maximum magnetic latitude = 68° boundaries of the model.

The time required for your computer to predict the fluence for orbit "Sample" is recorded in the ASCII benchmark file called SAMPLE.BEN. Following is a copy of the bench mark file for Sample used on a 66 Mhz 486 GATEWAY computer at the Phillips Laboratory.

***** Time increment = 136.34 seconds.
13:47:53.40 --> LOKANGL started
13:47:55.98 --> LOKANGL finished
Number of points = 635
13:47:56.09 --> MAGMODEL started
13:48:04.28 --> MAGMODEL finished
13:48:04.28 --> TIMEBINS started
13:48:04.66 --> TIMEBINS finished
13:48:04.72 --> FLUXDATA started
13:48:24.82 --> FLUXDATA finished

Time increment is the step size chosen by CRRESPRO to calculate ephemeris and fluence. This time was chosen so that the satellite swings through approximately 2° arc at perigee. See Appendix C for calculations. LOKANGL took 2.58 seconds to run, MAGMODEL took 8.19 seconds, TIMEBINS took 0.38 second, and FLUXDATA took 20.1 seconds. The rest of the time was spent waiting for user input and was not considered in the estimated run time of 1.1 minutes. The actual time taken was 30.49 seconds while the estimate was for 1.1 minutes. The estimate tends to be a worst case estimate. By comparing your benchmark file to the one shown above you can calculate the speed of your computer versus the benchmark computer. This ratio applies to the estimated run time.

Appendix B

Format of FLUX_MOD.## Files

The FLUX_MOD.## files contain data binned by L shell and B/B_0. Any rate data such as flux or dose rate can be put into these files, provided the following format is used:

- The filename must be FLUX_MOD.## (## = 00 to 99)

- The file structure is of the type:

-- BORLAND PASCAL

```
Type
  FluxRecord = record
      MainTitle,
      SubTitle,
      Units      :  String[136];
      d          :  Array[1..90,1..34] of Single;
  end;
```

-- ANY OTHER LANGUAGE

```
      MainTitle,
      SubTitle,
```

Units : Each is an array of 136 eight bit bytes or characters. The first byte contains the number of characters in the array (0 to 136). The following bytes contain the characters in the array.

d : This is the data. Each bin is a 4 byte real number following the convention set by the Intel math coprocessor. The data is binned in a two dimensional array of 1 to 90 (L shell) by 1 to 34 (B/B_0). Consecutive B/B_0 bins occupy consecutive spaces in memory.

- The files have four different groups of information.

-- The first three groups are strings. **MainTitle** and **SubTitle** are strings of characters that are displayed as the two title lines by the utility DIPOLE.EXE. **Units** is the string displayed by DIPOLE.EXE near the scale to identify what type of data is displayed.

-- The fourth group is the data. **d** is a two dimensional array of 1 to 90 (L shell) by 1 to 34 (B/B_0) bins.

--- I is the index associated with L shell, and ranges from 1 to 90. The limits of bins with index I are: $0.95+0.05I\ R_E \leq$ L shell $< 1.00+0.05I\ R_E$

--- J is the index associated with B/B_0, and ranges from 1 to 34. The limits of bins with index J are:

$B_{J-1} \leq B/B_0 < B_J$;

$B_{0\ldots34}$ = 1.000, 1.004, 1.020, 1.046, 1.085, 1.140, 1.200, 1.300, 1.400, 1.520, 1.690, 1.880, 2.100, 2.400, 2.730, 3.130, 3.670, 4.350, 5.020, 6.100, 7.410, 9.088, 1.129e1, 1.422e1, 1.816e1, 2.356e1, 3.107e1, 4.147e1, 5.723e1, 8.025e1, 1.154e2 1.707e2, 2.607e2, 4.134e2, 6.846e2. (where e# indicates ($\cdot 10^{\#}$).)

--- The values of B_J are such that the limits B_0 to B_{34} c[illegible] approximately $\pm 68°$ magnetic latitude in a dipole field.

Appendix C

Calculations Used to Create Element File

We give here the equations used to 1) calculate the time step used in LOKANGL.EXE, 2) convert solar elements to mean orbital elements, and 3) eliminate invalid orbits, namely those that are not closed or that pass close to or beneath the surface of Earth. Two constants specific to Earth that are used throughout are μ, the gravitational constant times the mass of Earth, and R_E, the radius of Earth assuming Earth is spherical. These values are:

μ = 398601.2 km^{3}sec^{-2},
R_E = 6378.145 km.

(1) Time Step Calculation:

If Position/Velocity Elements are used where

$$r = \sqrt{r_x^2 + r_y^2 + r_z^2} \quad , \quad v = \sqrt{v_x^2 + v_y^2 + v_z^2},$$

then define the three quantities, a, h, and e as

$$a^{-1} = \frac{2}{r} - \frac{v^2}{\mu} \quad , \quad h = |\vec{r} \times \vec{v}| \quad , \quad e^2 = 1 - \frac{h^2}{\mu a} \quad .$$

Here a is the semimajor axis in km, h is the angular momentum in km^2/sec, and e is the eccentricity.

If Mean Orbital Elements are used, the eccentricity e and the mean motion M_m in revolutions per day are given as elements. The semimajor axis a and the magnitude of the angular momentum h are given by:

$$a^3 = \mu[(12 \cdot 3600)/(\pi M_m)]^2 \quad , \quad h^2 = \mu a(1 - e^2) \quad .$$

In terms of a, h, and e, the time step T_s, which is approximately equal to the time to traverse 2° arc at perigee is:

$$T_s = a^2(1 - e^2)h^{-1}\frac{\pi}{90} \quad .$$

In this calculation $d\Theta/dt$ at perigee is assumed to be constant over the 2° arc.

(2) To Convert Solar Elements to Mean Elements:

Use the convention day = 1 on 1 January 1992.

Define the following quantities:

$r_a = A_a + R_E$;

$r_p = A_p + R_E$; A_a and A_p are altitudes from the surface of Earth in km;

$H_e = 6.594703 + 0.0657098243 \cdot day + 1.00273791 \cdot Hr$ [U.S. Naval Observatory, 1992];

$\Theta_a = (H_a + 12)*\pi/12$, where H_a is local time of apogee;

$\Theta_i = (H_i - 6)*\pi/12$, where H_i is local time of maximum inclination.

Then the six elements are:

inclination, i, is given;

eccentricity, $e = (r_a - r_p) / (r_a + r_p)$;

mean anomaly, M = 180° (satellite is at apogee when elements are defined);

squared mean motion, $n^2 = \mu/[\frac{1}{2}(r_a + r_p)]^3(12 \cdot 3600/\pi)^2$;

right angle of ascending node, $\Omega = 15(H_i - 6 + H_e)$;

argument of perigee, ω, $\cos(\omega) = \cos(\Theta_a)\cos(\Theta_i) + \sin(\Theta_a)\sin(\Theta_i)$.

(3) Check Elements for valid orbit:

The orbit is valid if:

a) the orbit is closed: $0 \leq e^2 < 1$;

b) perigee is not below the surface of Earth: $a(1-e) \geq 6400$ km.

Appendix D

Format of Ephemeris Files

The geographic ephemeris files end with the extension "SPH." These are binary files that are output from LOKANGL.EXE. Each record of the file specifies the position of a satellite, and the time interval between all records is constant (T_t is in Appendix C). These files are input by MAGMODEL.EXE to produce the magnetospheric ephemerides.

Each record of the file contains, in the following order:

year	: 2 byte integer
day	: 2 byte integer
second	: 4 byte real
latitude	: 4 byte real (deg)
longitude	: 4 byte real (deg)
radius	: 4 byte real (km)

The magnetospheric ephemeris files end with the extension "MAG." These are binary files that are output from MAGMODEL.EXE. Each record of the file specifies the position of a satellite in Earth's magnetic field, and the time interval between the records is constant (T_t). The requirement for a constant time step is set by TIMEBINS.EXE. These files are input by TIMEBINS.EXE to produce files indicating how much time the orbit spends in the magnetospheric bins defined for the flux models (see Appendix B).

Each record of a ".MAG" file contains, in the following order:

L shell	: 4 byte real (R_E)
B/B_0	: 4 byte real

Open field lines are indicated by an L shell of -1 or L shells > 15 R_E.

The last record of each file contains, in the following order:

-100 : 4 byte real

TimeStep : 4 byte real (time interval between steps)

LOKANGL.EXE can be bypassed by creating a ".SPH" ephemeris file of the proper format. CRRESPRO will still request orbital elements so you must generate a dummy element file, but CRRESPRO will not execute LOKANGL.EXE if the ".SPH" file exists. In the same way, a different magnetospheric model can be used by creating a ".MAG" file of the proper format. CRRESPRO will still request orbital elements, and will run LOKANGL.EXE (if a ".SPH" file does not exist), but it will not execute MAGMODEL.EXE.

Appendix E

CRRESPRO Support Programs

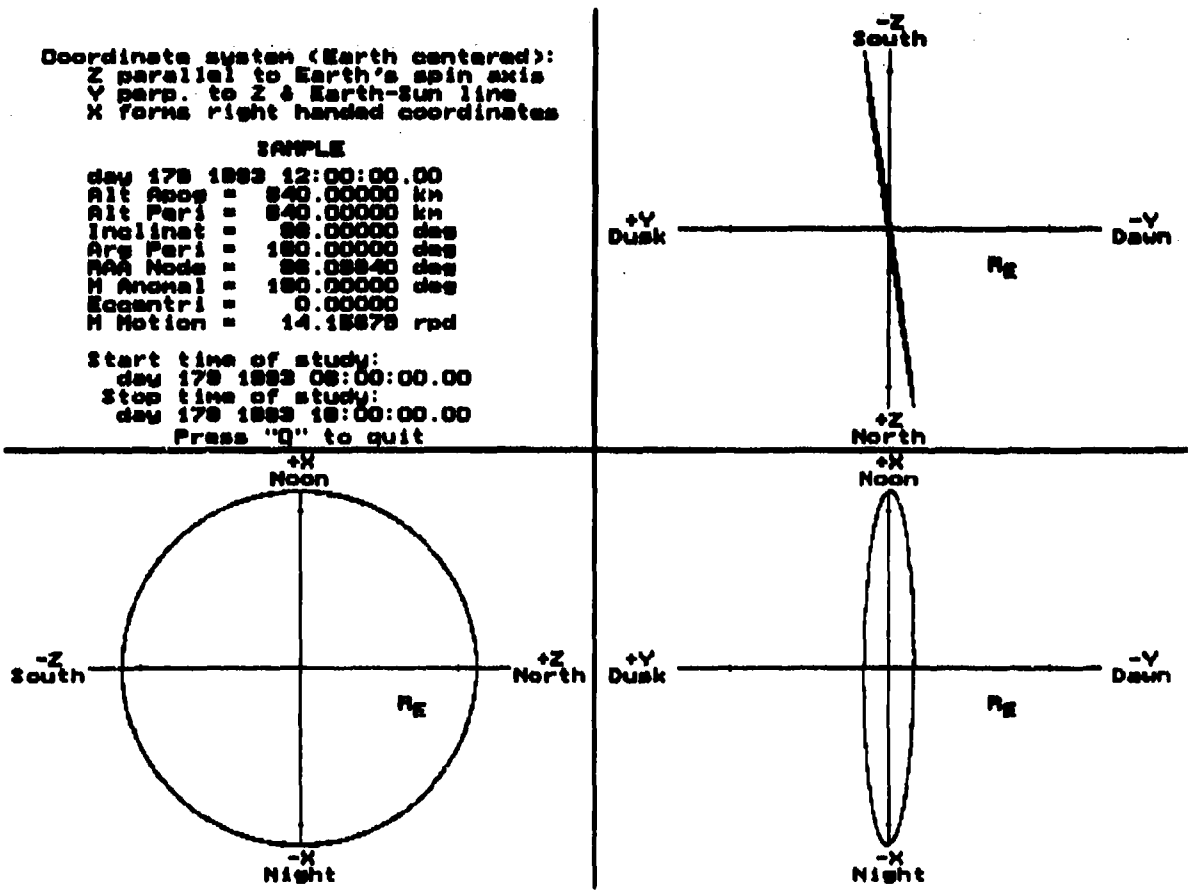

Figure E1. ORBIT.EXE Screen.

ORBIT.EXE - This is a display utility program that works on a color EGA/VGA monitor. It is called by CRRESPRO, but may also be called from the command line. This program reads the ".SPH" files, and will also read the ".DAT" files if they exist. When calling ORBIT.EXE from the command line, the name of the run must be included on the command line. The name of these files may include a path, but not an extension. If one typed "**ORBIT \ORB\SAMPLE**," the data file SAMPLE.SPH in the directory "\ORB" would be displayed. If SAMPLE.DAT exists then orbital elements read from that file would be displayed in the upper left corner. Figure E1 shows a screen capture of ORBIT.EXE using the files created in the sample session of Appendix A. The upper left corner shows information about the orbit drawn. In the coordinate system used (see Figure E2), **Z** points along Earth's spin axis and is positive toward the north pole, while **Y** is perpendicular to **Z** and the Earth-Sun line and is positive towards dusk. **X** completes the right handed coordinate system and goes through the noon meridian. The lower right-hand corner of Figure E1 shows the orbit projected into the XY plane. Tick marks show integer numbers of R_E. The other two corners show the orbit projected into the XZ and YZ planes. The orientation of the coordinates follows drafting convention where the figure in the lower right corner is the top view and the other two figures are side views. Pressing "**Q**" exits the program.

MAGMODEL.EXE - This program uses the IGRF85 and Olson-Pfitzer Static Magnetic Field Model IBM PC Fortran routines developed by Karl Pfitzer (1991). To use this code two command line parameters are required. The first is the path of the source file (including name and extension), and the second is the path of the destination file (including name and extension). The source file is a geographic ephemeris file, and the destination file is a magnetospheric ephemeris file. The formats of both these files are described in Appendix D.

DIPOLE.EXE - This program displays the flux data in the FLUX_MOD.## files The data is placed spatially on the screen as it would look if Earth's magnetic field were a dipole. (The image will not be proportioned correctly if an EGA card is used). Figure E3 shows a copy of the screen when DIPOLE.EXE is displaying the orbit generated in Appendix A. The figure is shown in gray scale, but the program is displayed in color. The following description explains what is seen here (in gray scale). The half circle on the left side of the screen represents Earth with the magnetic axis pointing straight up. Gray scales represent intensity of flux. Higher flux tends toward the darker shading, and lower flux tends toward the lighter shading. If the flux is above the color scale, it will be shown as black, and if the flux is below the color scale or there is no data, it will be shown as light gray. The display on the computer screen will show Earth as a cyan colored half circle. Color scales represent the intensity of flux. Higher flux tends toward red and lower flux tends toward blue. Flux above the color scale is shown in white,

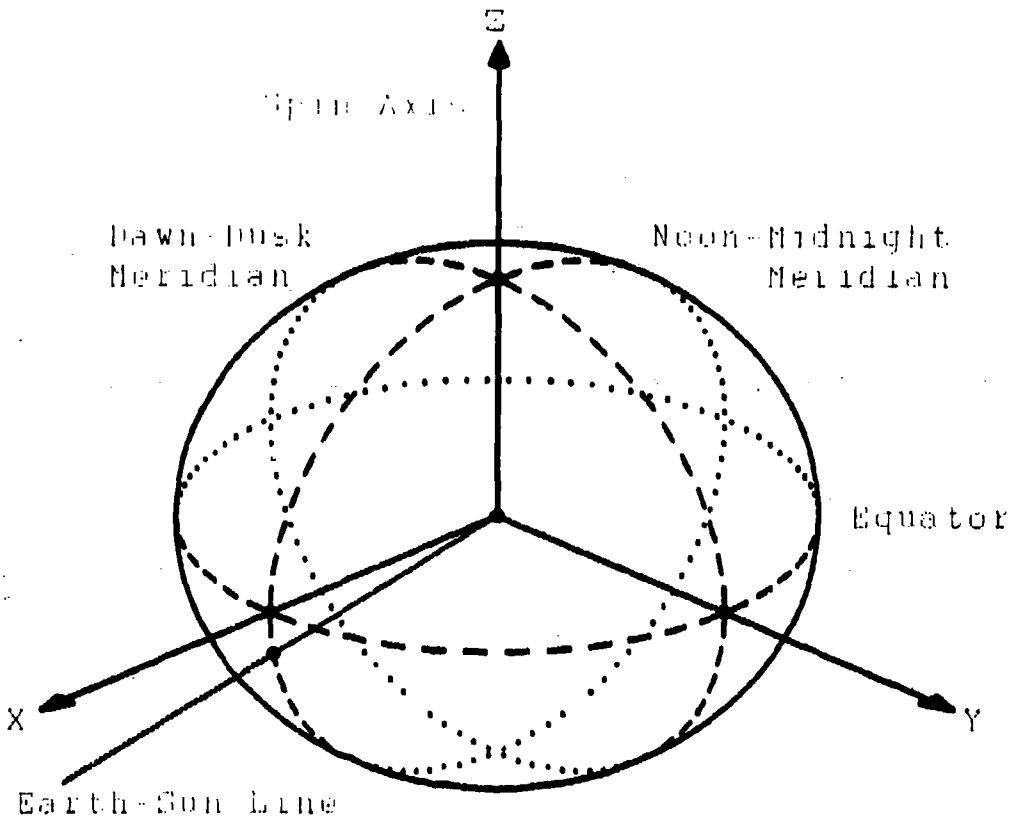

Figure E2. Coordinate System Used for ORBIT.EXE.

and flux below the color scale is shown in gray. The space bar calls up an options menu. The color scale can be reset and can also be changed from a log to a linear scale. One can move to a higher (lower) flux model by pressing the plus (minus) key. Pressing "Q" quits the program. The orbit in L shell versus B/B_0 is plotted as a black line on the upper quadrant of the flux data. The orbit is plotted in only one quadrant because B/B_0 contains no information about +/- latitude. This causes the orbit to be folded into the upper quadrant. In Figure E3, the orbit covers the area from Earth's surface to beyond the L cutoff of 5.5. The flux model in Figure E3 shows omnidirectional flux for 26.3 MeV protons during the active time period. Two proton belts with peaks at 1.5 and 2.3 R_E clearly show in the figure.

The orbit plot superimposed on the flux data can be used to analyze the effectiveness of CRRESPRO for the given orbit. Portions of low orbits may actually be drawn below Earth's surface on the plots. This results from the fact that Earth is not actually spherical, the magnetic field is not actually dipolar, and the center of the magnetic field is not at the center of Earth. The valid range of the PROTEL data can be seen clearly from looking at the flux plots.

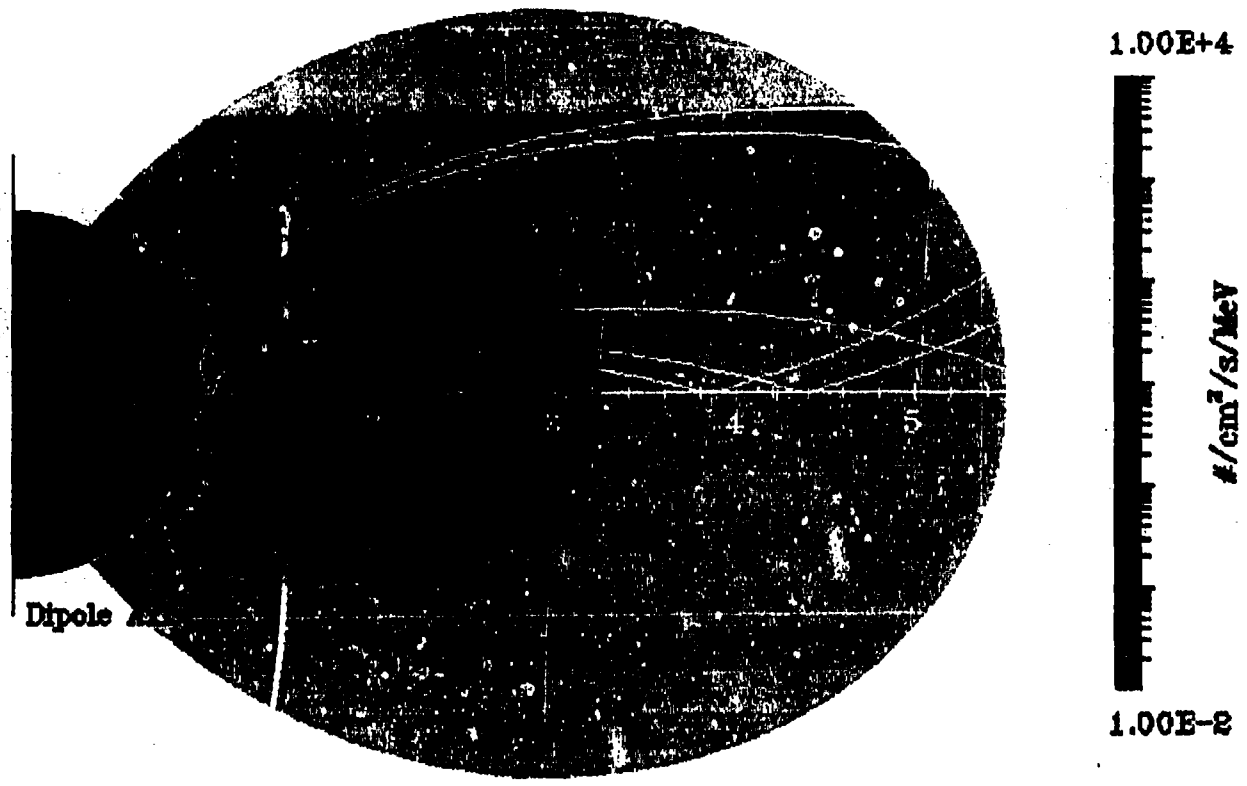

Figure E3. DIPOLE.EXE Screen Displaying SAMPLE.MAG Orbit.

DIPOLE.EXE can be run from the command line by typing "**DIPOLE.**" Dipole will ask for the file number to be displayed, and will then graph the data. The file number can also be specified on the command line. To show FLUX_MOD.09 one would type "**DIPOLE 9.**" A second command line parameter can be included to show an orbit superimposed on the flux map. The second parameter must be the path (including name and extension) of a magnetospheric ephemeris file. The file must be of the format given in Appendix D.

Appendix F

Contents of SAMPLE.DAT

CRRESPRO Prediction Utility - SAMPLE

Element time: day 130 1991 07:59:59.71
Alt Apog = 32999.99933 km Alt Peri = 350.00066 km
Inclinat = 18.00000 deg Arg Peri = 180.00000 deg
RAA Node = 47.29340 deg M Anomal = 180.00000 deg
Eccentri = 0.70815 M Motion = 2.48032 rpd

Start time of study: day 130 1991 08:00:00.00
Stop time of study: day 131 1991 08:00:00.00
Time of study is 0.99930 days (44.0% of orbit out of range)

Omnidirectional fluence/year (#/cm^2/MeV):

Ave Energy	Quiet	Active
1.5 MeV	1.61E+0013	1.66E+0013
2.1 MeV	6.18E+0012	7.53E+0012
2.5 MeV	3.33E+0012	4.65E+0012
2.9 MeV	1.70E+0012	2.87E+0012
3.6 MeV	8.45E+0011	2.08E+0012
4.3 MeV	3.90E+0011	1.06E+0012
5.7 MeV	1.25E+0011	3.49E+0011
6.8 MeV	6.03E+0010	1.76E+0010
8.5 MeV	3.01E+0010	7.29E+0010
9.7 MeV	2.00E+0010	3.85E+0010
10.7 MeV	1.50E+0010	2.45E+0010
13.2 MeV	1.06E+0010	1.21E+0010
16.9 MeV	5.67E+0009	5.26E+0009
19.4 MeV	3.05E+0009	2.89E+0009
26.3 MeV	2.16E+0009	2.05E+0009
30.9 MeV	1.47E+0009	1.52E+0009
36.3 MeV	1.11E+0009	1.21E+0009
41.1 MeV	5.88E+0008	6.72E+0008
47.0 MeV	4.08E+0008	4.59E+0008
55.0 MeV	4.70E+0008	5.12E+0008
65.7 MeV	4.67E+0008	4.39E+0008
81.3 MeV	3.21E+0008	2.97E+0008

Integral Omnidirectional Fluence/year (#/cm^2) to 90.4 MeV

Energy	Quiet	Active
1.1 MeV	1.85E+0013	2.26E+0013
1.9 MeV	5.68E+0012	9.32E+0012
2.3 MeV	3.20E+0012	6.31E+0012
2.7 MeV	1.87E+0012	4.45E+0012
3.1 MeV	1.19E+0012	3.30E+0012
5.5 MeV	3.53E+0011	7.51E+0011
5.9 MeV	3.03E+0010	6.11E+0011
7.7 MeV	1.95E+0011	2.94E+0011
9.3 MeV	1.46E+0011	1.78E+0011
10.1 MeV	1.30E+0011	1.47E+0011
11.3 MeV	1.12E+0011	1.17E+0011
15.1 MeV	7.22E+0010	7.13E+0010
23.7 MeV	4.60E+0010	4.65E+0010
28.9 MeV	3.47E+0010	3.58E+0010

32.9 MeV	2.89E+0010	2.98E+0010
40.2 MeV	2.07E+0010	2.09E+0010
43.2 MeV	1.90E+0010	1.89E+0010
50.8 MeV	1.59E+0010	1.54E+0010
59.2 MeV	1.19E+0010	1.11E+0010
72.2 MeV	5.84E+0009	5.40E+0009

NASA AP8MAX Integral Ommidirectional Fluence for > 90.4 MeV protons:
7.39E+0009 protons/cm^2